RESISTANCE TO PULL-OUT OF CHILEAN RIVERINE SPECIES: EVIDENCE FROM LABORATORY EXPERIMENTS

G. Piqué*[a,b], L. Mao[b,c], P. Becerra[b]

[a] Escuela de Agronomía, Facultad de Ciencias Agronómicas y de los Alimentos, Pontificia Universidad Católica de Valparaíso, Quillota, Chile[1]

[b] Departamento de Ecosistemas y Medio Ambiente, Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Santiago, Chile

[c] School of Geography, University of Lincoln, Lincoln, UK

* Corresponding author: gepique@uc.cl

[1]Present address for the corresponding author G. Piqué has changed from 'Pontificia Universidad Católica de Chile' to 'Pontificia Universidad Católica de Valparaíso'. Current e-mail: gemma.pique@pucv.cl

ABSTRACT

Vegetation growing in river bars and banks determines the morphological processes in river channels. The presence and dynamics of riverine vegetation depend on the magnitude and frequency of floods able to change morphology and uproot plants, and on the plant's resistance to pull-out. A series of pull-out experiments were carried out with the objective to determine the resistance of riverine vegetation to be uprooted and its effects on river-bed dynamics. Nine riverine species were used for the experiment: seven of them are native from Chile, and the other two are exotic and invasive in Chilean environments. A total of 200 specimens were transplanted in a substrate simulating a bar of a gravel-bed river, and after 7 months they were individually pulled-out, and the force and time needed to uproot the plant quantified. Data were analysed by means of generalised linear models (GLM) and linear regressions, and force-time curves were interpreted and related to the root morphology of the species. GLM results showed that resistance values are dependent on root and plant physical characteristics, and by the factor species. Among the species studied, the three species showing higher resistance values were native, while the less resistant was an exotic invasive species. The time needed to uproot the individuals did not seem to be influenced by plant parameters nor by the factor species. Root architecture seemed to have an effect on plant pull-out resistance and uprooting rapidity, being heart-shaped roots the ones that registered higher resistance values. Despite this, when incorporating flow strength on the findings, the exotic invasive ones seemed to be some of the more resistant to uprooting. The findings of this paper contribute to the better understanding of river vegetational and sedimentary dynamics, and are useful for parameterising the modelling of fluvial landscapes evolution and for the design of river restoration projects.

Keywords: pull-out resistance; vegetation uprooting; gravel-bed river; central Chile

1. INTRODUCTION

Riparian vegetation exerts a great influence on river channel morphology by stabilising and trapping sediments, and originating abundant and diverse fluvial forms (Gurnell, 2014). During flood events, vegetation may be removed from bars, margins, and floodplains, thus vegetation dynamics depend on the occurrence and magnitude of these disturbances (Gurnell et al., 2012). The complex interaction between flow and vegetation has been assessed in several studies. For instance, Bankhead et al. (2017) described both the driving and resistance forces acting on riverine vegetation when immersed. They identified water flow as the driving force acting on vegetation, and vegetation root anchoring as the main resisting force to uprooting. The complex series of feedbacks and interactions between vegetation and fluvial landforms processes was conceptualized in terms of "fluvial biogeomorphic succession" (Corenblit et al., 2007). This bi-directional interaction occurs at all stages of vegetation growth, but young seedlings are more susceptible to be detached by high flow pulses and floods, while mature individuals are more capable of recovering after partial uprootings due to floods (Crouzy, 2014). This generates a selective removal of the weaker vegetation on bars and margins (Perona et al., 2012; Crouzy et al., 2013).

Edmaier et al. (2011) classified the mechanisms of plant uprooting in two types: I) uprooting of the whole plant due to flow drag forces, and II) uprooting due to local sediment erosion around the plant, which exposes the roots and reduces root anchoring. According to these authors, type I detachment mechanism occurs in a very short time, and depends on root amount and characteristics (e.g. diameter, length, strength). Type II detachments occur more gradually, since root-anchoring forces are progressively reduced due to the higher exposure of roots after an erosion period. The resistance of riparian vegetation to pull-out has been quantified both in the field (e.g. Karrenberg et al., 2003; Abernethy and Rutherfurd, 2001), and in laboratory conditions (e.g. Xavier et al., 2010; Edmaier et al., 2015). Giadrossich et al. (2017) described the variety of experimental methods that have been used to measure root strength in hillslopes. Among them, three instruments were found to be applied in riverine environments: i) root-pullers to remove the entire plant from the substrate (e.g. Karrenberg et al., 2003; Bankhead et al., 2017); ii) root-pullers to pull up individual roots from

the substrate (e.g. Abernethy and Rutherfurd, 2001; Bankhead et al., 2017); and iii) tensile testing machines to stretch individual root segments extracted from soil until their failure (e.g. Edmaier et al., 2014; Capilleri et al., 2016). The three approaches use apparatus based on similar technology: i.e. plants or roots attached to a load cell or a transducer and to a puller device at the other end. Numerous experiments showed that the pull-out resistance of plants and roots in stream banks is influenced by specific specimen characteristics: e.g. stem or root diameter (Bankhead et al., 2017; Osman et al., 2011; Calvani et al., 2019), number of roots (Edmaier et al., 2011), or root length (Bywater-Reyes et al., 2015). However, few focused on the time required to uproot a specimen. Besides plant characteristics, sediment material and substrate moisture also affect plant resistance to pull-out (Pollen, 2007). In this sense, less sediment moisture content implies greater force to uproot plants (Edmaier et al., 2014); and in riverine non-cohesive environments, higher pull-out resistances are observed in sand river-beds compared to gravel-beds (Karrenberg et al., 2003).

River channels are specially fragile and susceptible to vegetation invasions (Hood and Naiman, 2000; Castro-Díez and Alonso, 2017). The high presence and spread of exotic species in fluvial corridors are frequent in anthropogenic disturbed rivers (Richardson et al., 2007; Arianoutsou et al., 2010). At the same time, rivers constitute an easy way for seeds and propagules to spread by water (Pyšek and Prach, 1994; Richardson et al., 2007). Moreover, floods can contribute to a higher spreading of the seeds of invasive species by increasing the availability of nutrients and by the disturbances of native vegetation (Čuda et al., 2017). Among the wide range of invasive species, Australian *Acacias* are known to be invasive worldwide (Le Maitre et al., 2011) and, in particular, *Acacia dealbata* and *Acacia melanoxylon* are common in Chilean fluvial environments (Fuentes-Ramírez et al., 2010; Batalla et al., 2018). To the knowledge of the authors, it is unknown whether riverine exotic species differ from natives in the resistance to pull-out. Although riverine native species should have some resistance to uprooting by floods, a higher resistance to pull-out by riverine exotic species may explain their important abundance in fluvial habitats.

The main objective of this study is to determine the resistance of riverine vegetation to be uprooted and its effects on river-bed dynamics. Specific objectives of the paper are: i) to determine the

100 influence of root characteristics and root morphology on the species resistance to uprooting, ii) to
101 study the effects of different hydrological conditions on the resistance to uprooting, and iii) to
102 assess whether exotic invasive species are more resistant than native species. To respond to the
103 objectives, the uprooting resistance of 9 species from Chilean riparian environments was measured
104 in a series of plant pull-out experiments in controlled conditions. In order to reproduce similar
105 conditions found in the field, the uprooting experiments reproduced the type I erosion defined by
106 Edmaier et al. (2011) on young individuals growing on a non-cohesive substrate simulating a
107 gravel-bed river.

108 **2. EXPERIMENTAL DESIGN AND METHODS**

109 **2.1. Experimental design**

110 An assortment of 200 individuals of 9 bushy and tree species commonly found in Chilean riparian
111 environments were used in the experiment (Table S1 in Supplementary material). We selected
112 species commonly growing in the Mediterranean region of Chile. Among them, 7 are native from
113 Chile (i.e. *Aristotelia chilensis*, *Cryptocarya alba*, *Escallonia illinita*, *Fuchsia magellanica*,
114 *Lithraea caustica*, *Maytenus boaria*, and *Quillaja saponaria*), and 2 are exotic (i.e. *Acacia dealbata*
115 and *Acacia melanoxylon*). Both were introduced for ornamental purposes in the late 1800s (*A.*
116 *dealbata*) and early 1900s (*A. melanoxylon*), and have a high invasive potential (Fuentes et al.,
117 2014). Among native species, *Escallonia illinita* and *Fuchsia magellanica* grow exclusively in
118 riparian habitats throughout the Mediterranean region of Chile, while the other species may also be
119 found in other habitats of this region. Both exotic species also grow in riparian habitats in the
120 Mediterranean region of Chile.

121 Plants were selected in order to be as much similar in terms of stem diameter and height between
122 individuals of the same species at the beginning of the experiment. All specimens were 1 year old,
123 except the *Acacia dealbata*, which germinated a year before. Specimens were growing on small
124 cylindrical plastic bags (volume between 400 and 800 cm^3).

In order to simulate the conditions of plants growing on alluvial bars of a common gravel-bed river, the specimens where transplanted on much larger plastic growing bags (diameter = 22.5 cm, height = 37 cm, volume ~ 14,700 cm^3) filled with a substrate composed mainly of sand, gravels and cobbles (D_{50} = 15.67 mm; D_{max} class = 31.5 mm; Fig. 1), thus replicating a non-cohesive environment.

Transplanted individuals were grown inside a nursery during almost 7 months (from 25-31 of July 2018 to 24-30 of January 2019, Fig. 2a and 2b) to allow for the roots to develop during most of an entire growing season. All plants were equally and regularly watered when needed, depending on the weather conditions and humidity of the substrate. The growth of all individuals was monitored monthly by measuring their stem diameter and height. Moreover, the root systems of one individual per species were scanned using WinRizho® software before transplanting and at the end of the experiment to have an approximation of root growing during the period by measuring the root length, root area, average root diameter, and root volume.

The plant pull-out experiments were performed between the 25th and 30th of January 2019. The pull-out mechanism (Fig. 2c, 2d and 2e; and Video 1 and 2 in Supplementary material) consisted on a load cell, connected to an electric winch located at the top of a tripod, and attached to the base of the stem of a specimen, by means of a carabiner and wrap tape. The load cell (PCE-FB 5K, PCE-Instruments®) measured at 0.1-second intervals the strength offered by the roots during the pull-out experiments, resembling to the previously done in similar experiments (Osman et al., 2011; Bankhead et al., 2017). Pull-outs were performed vertically and at the same distance in order to ensure the same treatment to all individuals, despite the effects of pull angle on the strength lecture are minimal (Gupta et al., 2008). The experiments allowed to obtain continuous curves of the strength needed to remove the plant over time. From this data, the maximum resistance of the individual (R_{max}) and the time needed for removal (T_{to_max}) were calculated. Individuals were also measured both in their aerial part (stem diameter and height) and roots (diameter at 2 cm depth), and weighted and dried in the oven (45ºC, 72 h) to obtain dry biomass.

2.2. Data analysis

2.2.1. Evaluation of plant resistance to pull-out.

Overall, successful pull-out runs were completed for 180 individuals. Four different plant parameters were selected as predictors or independent variables: root cross-sectional area at 2 cm depth (RA, calculated from root diameter measurements), root biomass (RB), total biomass (TB), and ratio between aerial and root biomass (A-RB). These independent variables were related to plant pull-out maximum resistance recorded during the removal (R_{max}), and time needed from the initiation of the pull-out to the maximum resistance value (T_{to_max}). Both R_{max} and T_{to_max} were obtained from the force-time curves of every individual.

As dependent data was not normally distributed, Generalised Linear Models were performed (GLM, multiple regression analysis, gamma distribution and log link function), including 'species' as grouping factor to evaluate whether the species affects significantly the relation between variables. Another GLM was used (separate-slope model) in order to evaluate whether the interaction between variables depends on the species. Finally, to determine the specific interaction of each species on the response variables, GLM per species (multiple regression) were conducted separately.

2.2.2. Evaluation of differences between species

The same variables mentioned before (RA, RB, TB, A-RB) were used to evaluate whether some species were more resistant to pull-out. In this case, the analysis was conducted considering only the mean value per species. In order to explore the role of root architecture on plant resistance to pull-out, the root of one specimen per species (randomly selected before the experiment) was scanned in order to have three additional independent variables: i.e. root length (RL), average root diameter (ARD), and root volume (RV).

All dependent variables followed a normal distribution, so the relation between dependent and independent variables was analysed using correlations and simple regressions. However, in order to be consistent with previous analyses, GLM were also performed (multiple regression, normal distribution, identity link function).

178 ## 3. RESULTS

179 Each pull-out experiment produced a force *vs*. time curve, as those depicted in Fig. 3. Each curve
180 starts from the same origin, and then the force-time curves tended to have a homogeneous slope in
181 the rising limb. The maximum resistance (R_{max}) corresponds to the maximum force resisted by the
182 roots before breaking. The time needed to reach the peak (T_{to_max}) was computed as the time interval
183 from the first increment in resistance to the peak of the curve. The recession limb corresponds to the
184 phase of the experiment when the roots (and in some cases a pan of soil) were extracted. As
185 described in previous works (Bailey et al., 2002; Gregory, 2006; Edmaier et al., 2014), the recession
186 limb in some cases registered small peaks that corresponded to small root breaking or loosening
187 before the complete plant extraction.

188 ### 3.1. Pull-out resistance parameters

189 The maximum force needed to uproot the plants from their pots differed notably between species, in
190 terms of both mean values and variability (Fig. 4a). *A. dealbata* is the species that showed less
191 resistance to uprooting (mean = 22.64 N), while *E. illinita* was the species with higher resistance
192 values (mean = 72.63 N). The range of values was also variable between species, being *M. boaria*
193 and *E. illinita* those showing the larger variability (SD = ± 32.70 N and ± 24.69 N, respectively),
194 and *L. caustica* the species with less variability (SD = ± 7.65 N). The minimum force value
195 recorded was 2 N in an individual of *A. dealbata* while the maximum force (126 N) was measured
196 in an individual of *E. illinita*. Variability in T_{to_max} values was more homogeneous between species
197 (Fig. 4b). The highest mean T_{to_max} was observed in *M. boaria*, while the lowest in *Q. saponaria*
198 (0.778 s and 0.411 s, respectively). Intraspecies variability was wide in all cases, being *C. alba* the
199 species showing the lowest range of variability (SD = ± 0.248 s). The maximum value was
200 measured in an individual of *A. chilensis* (i.e. 0.18 s), while the minimum (i.e. 0.1 s) was observed
201 in individuals of all species except the *F. magellanica*.

202

3.2. Plant resistance to pull-out

Fig. 5 shows the maximum pull-out resistance values plotted against the selected plant predictor parameters. R_{max} increased significantly with RA, RB and TB (Table 1). The A-RB ratio did not have a significant effect on R_{max}, (not significant GLM p-values), which is also visible in the very scattered relationship between the two variables in Fig. 5c. The factor Species also significantly affected the response of a plant to a pull-out force (p-value <0.01). In turn, T_{to_max} was significantly influenced by RA and TB (Table 1), but in this case the factor Species did not have an effect on it.

Moreover, the interaction of Species and plant parameters had a clear influence on $R_{max,}$ but not on T_{to_max} (Table 2).

3.3. Species effect on the resistance to pull-out

The mean R_{max} was significantly correlated ($p < 0.05$) to mean RB, mean TB, RV, and RL (Table 3). These relationships followed a positive linear regression with $R^2 > 0.5$ in all four cases (Fig. 6). According to the linear regression analysis, T_{to_max} was not significantly correlated to any of the plant parameters (Table 3). Fig. 6 shows that *E. illinita*, *A. chilensis* and *M. boaria* were the species with higher values in plant parametres and R_{max}. Conversely, *A. dealbata* and *L. caustica* displayed in the bottom left part of the graphs, indicating that these were species with low values in plant parameters, and also low R_{max} values.

3.4. Root architecture and plant pull-out

Root architecture was assessed both visually and considering the parameters obtained with WinRizho® scans before and after the growing period (see Table S2 in Supplementary material for results). *F. magellanica* was, by far, the species showing higher values of both root length and volume before the transplanting (i.e. 72.37 m and 8.68 cm^3). After the growing period *A. chilensis*, *M. boaria,* and *E. illinita* were the species with longer roots (164.21 m, 133.74 m, and 113.93 m respectively), and higher root volumes (33.65 cm^3, 26.29 cm^3, and 36.48 cm^3, respectively). The small growth of *F. magellanica* roots was probably due to some setbacks during the growing seasons. Indeed, *F. magellanica* experienced also the slower growth of the stem if compared with

229 all the other species (Table S2 in Supplementary material). Growth in RL and RV for *F.*
230 *magellanica* individuals equalled 5.8% and 151.5%, respectively. Root increments in the other
231 species were >300% in RL, and >500% in RV.

232 The 9 species used in the experiment were classified into 4 groups, according to the extent and
233 geometry of their roots, based on visual observations and root scans data (Fig. 7). Group I included
234 those species with a short thick principal root, several medium-sized roots, and a dense fine root
235 network (i.e. *A. chilensis*, *E. illinita*, *F. magellanica*); Group II gathered the species with a long
236 thick principal root, some medium-size roots, and a fine root network (i.e. *A. dealbata*, *L. caustica*,
237 *Q. saponaria*); Group III included those species with a long thick principal root, few medium-size
238 roots, and a semi-dense fine root network (i.e. *A. melanoxylon*, *M. boaria*); and finally, Group IV
239 was composed of only one species (i.e. *C. alba*) which was characterised by a thick principal root
240 and a dense fine-medium root network. This group configuration is consistent with the observed in
241 the Fig. 8a (each colour represents a 'morphology group'), where *A. chilensis* and *E. illinita* show
242 high values and variability in the up-ramp SD curve, and *A. dealbata*, *L. caustica* and *Q. saponaria*
243 show low slope values and less variability in the up-ramp SD. *F. magellanica* was not displayed in
244 the upper part of the graph probably because this species had some growth setbacks, as stated
245 above. The lower Fig. 8b plots the accumulated increment of plant resistance per accumulated
246 increment of time. The curves with the highest slopes indicate that those species were extracted
247 faster than the ones showing less slope.

248 **4. DISCUSSION**

249 **4.1. Plants resistance to pull-out**

250 *4.1.1. Plant parameters defining resistance to pull-out*

251 The physical characteristics of the plants' rooting systems are determinant for their resistance to
252 uprooting. According to the results, the best descriptors for plant resistance to pull-out are RB, TB
253 and RA. Further good parameters to infer pull-out resistance are RL and RV. The statistically
254 significant relation between plant parameters and R_{max} is positive in all cases, meaning that higher

values of RA, RB, TB, RV and RL lead to increased R_{max}. Although this is the first quantification of this kind for riparian species in Chilean (and more generally south American) environments, this was somehow expected, as similar results were found in previous works (reported in the Introduction section; e.g. Hales et al., 2013; Edmaier et al., 2011, 2014; Bankhead et al., 2017; among others). The variable T_{to_max} is particularly influenced by RA and TB, which may be related to the size or the weight of the plant. T_{to_max} also depends on RL when considering mean values, probably related to the findings noted in previous analyses. Indeed, Edmaier et al. (2011) found that short roots were generally removed more easily than long roots. The species does not have an effect on T_{to_max}, nor as a single factor nor in interaction with other species. This could be due to the relevant existing high intra-species variability, which is evident in the high dispersion of data and lack of trends. Given that only Edmaier et al. (2011) focused before on plant resistance to uprooting, comparison with previous evidence is not possible at this stage.

Although some of the previous works compared the resistance to pull-out of different species (e.g. Karrenberg et al., 2003; Bankhead et al., 2017), none of these assessed a wide range of species typical of riverine environments. The importance of the factor "Species" on the resistance to pull-out has been statistically demonstrated in this work, both when it is considered as a single factor and in interaction with the selected plant parameters. This suggests the existence of species-specific traits that are responsible for the differences between species as, for instance, root morphology, growth rate, and stem flexibility (e.g. Bornette et al., 2008; Kamchoom et al., 2014; Calvani et al., 2019, respectively). In fluvial environments, characterized by frequent and sudden floods in which plants are subject to high-energy events, the three factors are relevant for determining their resistance to uprooting.

4.1.2. Root morphology and plant resistance to pull-out

Among the species-specific traits that could affect the resistance to uprooting, in this paper we focused in root morphology. Despite the existing difficulties and challenges related to root characterisation (Stubbs et al., 2019), we visually classified the species used in the experiment in four groups according to their root morphology. Group I gathered species showing the highest

282 values of RB and TB, which were the parameters with the greater influence on pull-out variables (as
283 shown by the GLM analyses). At the same time, these species also showed the highest R_{max} values.
284 *F. magellanica* showed lower values than *A. chilensis* and *E. illinita* probably because the water
285 requirements of these species were higher than the average amount supplied during the growing
286 period. Also, the upper parts of the roots of a few specimens of *F. magellanica* were partially
287 affected by *Pseudococcus viburni* and ants that probably weakened the plant, causing at least 16
288 individuals plants to loose leaves (7 without any leaf and 9 with some leaves) and grow very slow.
289 Group I roots were formed by a short thick principal root that divides into several (2 to 6) medium-
290 sized roots. Probably, the medium-sized roots contributed to a high anchorage to the substrate since
291 there were more attachment points. According to Mickovski et al. (2007), the presence and depth
292 position of lateral roots have also an effect on the pull-out resistance, which could be reproduced by
293 the root geometry described for the species in Group I. Kamchoom et al. (2014) also identified the
294 heart-shaped roots (similar to roots of Group I) as the most resistant to pull-out. Groups II, III and
295 IV were characterised by having one tap root that determines root anchorage force. Group III
296 species had a higher density of fine-to-medium-sized roots than Group II, which would explain the
297 greater resistance to pull-out of Group III species. Zhang et al. (2018) proved that the density of fine
298 roots increased the soil shear strength, thus the resistance to be uprooted. Group IV (*Ca*) was the
299 one with shallower roots. Although Kamchoom et al. (2014) identified plate-shaped roots (shallow
300 roots, somehow similar to Group IV) as the less resistant, we found different results in this work. In
301 this group, fine-medium roots were thicker than the fine network of the other groups, which could
302 influence the measurements.

303 The relation curves between accumulated pull-out resistance until R_{max} and the accumulated time
304 until T_{to_max} (Fig. 8b) were indicators of the promptness of the plant uprooting. Those specimens
305 located in the right part of the graph registered slow velocities at the beginning of the pull-out, but
306 increased with time. According to the results of this work, species belonging to Group III were
307 representative for this extraction pattern, probably due to the high number of medium roots and the
308 high density of fine roots that prevented a rapid uprooting. Conversely, those individuals

represented in the left part of the graph were extracted in a less variable (although not constant) velocity of uproot. Some species of Groups I and II were represented in this side of the graph.

4.2. Interactions between flow strength and young riverine vegetation

Trying to relate the resistance to pull-out with the shear stress acting on a river bed that would be able to uproot the plants, we used an approach proposed by Calvani et al. (2019) for flexible juvenile seedlings. As in Eq. 4 of Calvani et al. (2019), we used the pull-out force (F_D, in N, as measured in our experiments in terms of R_{max}) to determine the shear stress acting on the river bed (τ_{bed}) as:

$$F_D = \tau_{bed}\,\pi\left(H_p D_p + \frac{A_l}{\pi} + L_e \sum_{i=1}^{N_g} D_{r,i}\right)) \quad \text{Eq. 1}$$

where D_p and H_p correspond to the diameter and height of the seedlings (in m) and were measured just before the pull-outs, and A_l corresponds to the foliage area (in m^2), roughly estimated by multiplying the number of leaves by the area of a leave (as the oval area calculation using length and width of an standard leave). The area of the roots exposed by erosion (L_e) that would be calculated based on the diameter (D_r) and number of roots exposed (N_g) was considered negligible in the first instance since no erosion occurred before the pull-outs. Estimations showed that, for the same R_{max}, the larger the A_l, the lower τ_{bed} was needed to uproot the individual. This is due to the higher surface of plants in contact with water, which make it more susceptible to be pulled-out by the flow.

Taking into account a rectangular cross-section in an exemplary gravel-bed river with slope 1%, we also computed the flow shear stress (τ, in N/m^2) for different water stages corresponding to three different hydrological conditions: high flows, floods, and extraordinary floods (0.2 m, 1 m, and 3 m of water depth above the substrate, respectively). Once computed, we then associated the estimated τ_{bed} values with the particle size movable at these water stages (i.e. 21.65 mm for the high flow, 108.23 mm for the flood, and 324.68 mm for the extraordinary flood). According to the calculations, the D_{50} used in the experiments (i.e. 15.67 mm) would be mobilised during a high flow pulse, while the maximum GSD class (i.e. it ranges between 31.5 and 45 mm) would move with

335 0.42 m of water depth above the substrate were plants were located. Regarding the individuals of
336 the experiment, none of them would have been uprooted during high flows, and individuals of only
337 some species (i.e. *A. dealbata*, *C. alba*, *F. magellanica*, *L. caustica*, *M. boaria, and Q. saponaria*)
338 would be uprooted in a flood of 1 m water depth (see Supplementary Figure S1). An extraordinary
339 flood would uproot individuals of all the species, being some of them completely removed (i.e. *C.*
340 *alba*, *L. caustica*, and *Q. saponaria*).

341 According to this exercise, although a flood of 0.5 m of water depth would mobilise a large part of
342 the substrate, the τ in this case would be far below the τ_{bed} values needed to uproot the individuals in
343 the experiment due to a lower root anchorage (Type II erosion described by Edmaier et al., 2011).
344 This finding indicates that erosion of the substrate would occur before the uprooting of these
345 specimens. However, if the equation from Calvani et al. (2019) was to be applied considering bed
346 erosion, the τ_{bed} needed to uproot the specimen would be lower. Indeed, as the roots become
347 exposed, there would be a larger portion of the plant area in contact with the flow (i.e. the exposed
348 roots), and the strength of the roots would diminish because bed erosion would contribute to the
349 loosening or detachment of the roots. In accordance to the results of the application of Eq. 4 from
350 Calvani et al. (2019) and the findings of Edmaier et al. (2011), both elements would make the
351 individuals more susceptible to be uprooted. Differences between species in the promptness of the
352 uprooting could not be evaluated since no real measurements were done in individuals with exposed
353 roots.

354 The most resistant species in the experiments do not coincide with the most resistant obtained when
355 considering flow strength. While in the former case only the root resistance was measured, in the
356 latter, the exercise incorporated both flow and the aerial part of the plant. These two elements
357 changed the interpretation of the results. When considering water flow and aerial biomass, the
358 exotic *A. dealbata* and *A. melanoxylon* were the most resisting species, likely due to the form and
359 configuration of their leaves (although generally abundant, leaves are small and altogether occupy
360 small areas). Although other intrinsic elements of the species could also affect the resistance to pull-
361 out (e.g. stem flexibility, leaves stiffness), their aerial morphological configuration could be an

362 explanatory factor for the abundance of e.g. *A. dealbata* in fluvial environments. However, it was
363 not possible to asses this fact in this experiment.

364 **4.3. Implications of vegetation growth and uprooting on river morpho-sedimentary dynamics**

365 The associated morphological changes in rivers related to vegetation presence have been widely
366 assessed (e.g. Hupp and Rinaldi, 2007; Corenblit et al., 2007). For instance, some of the main
367 responses to vegetation encroachment on river corridors are active channel narrowing and
368 deepening, reduction of the number of active channels, and changes in flow hydraulics (e.g. Gran
369 and Paola, 2001; Wang et al., 2015). Vegetation encroachment and growth stabilises river channel
370 by root anchoring and preventing erosion from very early stages of development (e.g. Abernethy
371 and Rutherfurd, 2001; Hubble et al., 2010). Vegetation prevents river bed from erosion by reducing
372 flow velocity due to increased roughness, and also probably due to the carpet-like protection that
373 the aerial part of the plants confer to the river bed when they bend (Termini, 2016).
374 The effect of vegetation on channel morphology depends on its type and density (Camporeale et al.,
375 2013), but also on the hydrological regime of the fluvial system (Gurnell et al., 2012). Hence,
376 magnitude and frequency of floods would finally determine the proportion of plants that detach and
377 the proportion that remain attached to the river bed. In non-disturbed river systems, the presence of
378 vegetation tends to be regulated by the hydrological regime (Corenblit et al., 2007). However, water
379 management for agricultural, industrial and urban uses usually implies the reduction of flowing
380 water or the modification of the discharge patterns. For instance, in semiarid areas or in regions
381 where agriculture has an important role, reservoirs are basic to maintain the economic sustainability
382 of the region. Below dams there is usually a lack of floods, and hence vegetation remains growing
383 indefinitely. In these cases, and especially in those where exotic invasive vegetation is present,
384 restoration actions may be useful to maintain fluvial dynamism and riparian habitat. For instance,
385 dammed rivers may release controlled high water discharges (flushing flows) with sufficient energy
386 to uproot very young specimens (Kui et al., 2014) located in river active bars (which should be
387 submerged during the release). Similar actions have been performed before to remove excess
388 vegetation encroachment on the river bed and proved to give good results (see the review of

389 Franklin et al., 2008). According to the results of our experiment, *A. dealbata* and *A. melanoxylon*
390 specimens have low resistance to uprooting, but are not the ones firstly removed due to their aerial
391 configuration, which could explain their high presence in river bars and margins. Despite being
392 difficult to detach, and although during these actions it is not possible to discern between species,
393 works should be performed in rivers where these species are present in order to prevent a wide
394 spread out. The younger the seedlings, the better would probably be the results of preventive
395 management actions, so they should be performed at a regular basis.
396 In the same sense, but in the opposite situation, e.g. need of bank stabilisation due to excess erosion,
397 the most resisting plants used in this experiment could be used to reinforce these banks. Among the
398 studied ones, *M. boaria* and *E. illinita* were the species resisting higher flow strengths, so they
399 could be used in these restoration actions in Chilean environments. Also, given that the
400 effectiveness in bank reinforcement actions is higher when multiple species are used for restoration
401 (Allen et al., 2016), a combination of the studied species could be used.

402 **4.4. Representativity of the experiments**

403 The reproduction of fluvial environments in small facilities is often complex because it implies the
404 scaling of both physical and ecological factors (Green, 2014). Also, scaling up the results from
405 experiments is still a challenge for earth scientists (Rice et al., 2010). The experiments of this study
406 reproduced substrate and vegetation interaction without the need of scaling none of the elements. In
407 these experiments, the sediment mixture reproduced fairly well the grain size distribution of
408 subsurface sediments in a gravel-bed river, ranging from pebbles to fine sand. Plants were also
409 realistic in age and size for the context of the study, so the results obtained in the pull-out
410 experiments can be considered representative for relatively active river bars with vegetation freshly
411 sprout from seeds. In this case, although the experiments were not reproduced using water flow, the
412 resistance opposed by the specimens was real and no correction was required to be compared to real
413 conditions. Although in real floods vegetation tends to bend in the flow direction and the pulling
414 angle is not vertical, previous experiments proved that the pulling angle does not substantially affect

415 the required force to uproot a plant (Gupta et al., 2008), so the results of this paper can be taken as
416 representative for real environments.

417 **5. CONCLUSIONS**

418 The experiments carried out contribute to the knowledge of the interaction between ecology and
419 fluvial geomorphology. The novelty of this study in comparison to other works using the same
420 methodology is the number of species used in the analysis. This provides knowledge beyond the
421 resistance to pull-out of different species, since the findings supply information for the design and
422 implementation of management actions of riverine ecosystems. The results of these experiments
423 show that despite the existing variability between individuals of the same species in terms of root
424 characteristics (e.g. root biomass, root length, diameter), the factor species is important when
425 studying plant resistance to erosion. When the analysis incorporates flow strength and the aerial part
426 of the specimen instead of root parameters, results change and the species showing higher uprooting
427 resistance vary. Given the importance of both factors: i) root morphology and dimensions (length,
428 volume, diameter), and ii) the aerial part of the individual, some works could be focused on the
429 construction of a model that combine these two elements. This would contribute to a more complete
430 and better understanding of the predominant forces and prevailing mechanisms in submerged
431 vegetation under flow stress.

432 The studied exotic invasive species did not show to be more resistant to uprooting than the native
433 ones, so the wide spread of this species may probably be due to other causes. Moreover, and despite
434 not having sufficient quantitative data to validate it, root morphology seems to be in some way
435 related to the resistance to erosion of a plant. Among the studied roots, those similar to heart-shaped
436 roots registered higher resistance values than those with a tap root. The effect of fine and medium-
437 sized roots could be also assessed, and those roots with a high density of small roots tend to offer
438 more resistance to pull-out. Further and longer experiments with a larger number of specimens of
439 different ages would be interesting to assess the evolution of the species resistance to pull-out and to
440 determine how the relation between root parameters (e.g. biomass, length, volume) and pull-out
441 resistance behaves with time. Similar experiments could also investigate the bending resistance of

plants, which could recreate more realistic flow-vegetation interactions. Analogous pull-out experiments could be performed in real river bars in order to evaluate the behaviour of native and exotic plants, and which environmental (or location) factors influence the most the plant resistance to pull-out.

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590

FIGURE CAPTIONS

Fig 1. Grain size distribution of the sediments used in the experiments. Fine sediments (< 2 mm) are included in one single class.

Fig 2. a) General view of the plant nursery days before the plant pull-out experiments; b) View of the plant before de pull-out; c) Plant pulling mechanism: tripod, electric winch and cell load; d) Detailed view of the carabiner attached to the stem; e) View of roots after the pull-out.

Fig 3. Examples of force-time curves of five individuals used in the experiment. Note that they are individual examples and that they cannot be taken as representative for each species. Inset graph shows graphically some of the concepts used along the article.

Fig 4. Maximum resistance (a) and pulling-out duration to reach max resistance (b) per species. For each case, the mean (black dot), the standard errors (box), and the standard deviation (whiskers) are shown.

Fig 5. Relation between plant parameters a) Root area, b) Root biomass, c) Aerial/root biomass, and d) Total biomass and maximum resistance measured for each individual. Note that data is treated all together and not separated per species (n = 180).

Figure 6. Mean maximum resistance as a function of selected plant parameters per species (n = 9, one per species). Only statistically significant relations ($p < 0.05$) are shown.

Figure 7. Roots of four individuals at the end of the growing period. a) *Lithraea caustica* (Group II); b) *Cryptocarya alba* (Group IV); *Maytenus boaria* (Group III); and d) *Fuchsia magellanica* (Group I).

Figure 8. a) Box plot for the standard deviation of the up-ramp pull-out curves per species. b) Example curves for the relative accumulated resistance to pull-out for the up-ramp curve *vs*. relative accumulated time per species.

Table 1

Table 1. GLM analysis to assess the influence of the selected plant parameters to pull-out resistance variables. Significant values are marked in bold (level of significance established at $p \leq 0.05$).

	Max resistance		**Time to max**	
	Chi- Square	**p-value**	**Chi- Square**	**p-value**
Root area	**23.41**	**<0.01**	**5.23**	**0.02**
Root biomass	**53.58**	**<0.01**	1.51	0.22
Total biomass	**26.38**	**<0.01**	**4.99**	**0.03**
Aerial/root biomass	1.10	0.29	0.13	0.71
Species	**46.25**	**<0.01**	12.45	0.13

Table 2

Table 2. GLM analysis to assess the interaction between the species (factor) and plant parameters (continuous predictors), as well as their influence on the pull-out variables. Significant values are marked in bold (level of significance established at $p \leq 0.05$).

	Max resistance		**Time to max**	
	Chi- Square	**p-value**	**Chi- Square**	**p-value**
Species × Root area	**92.35**	**<0.01**	15.26	0.08
Species × Root biomass	**36.00**	**<0.01**	9.51	0.39
Species × Total biomass	**25.13**	**<0.01**	7.15	0.62
Species × Aerial/root biomass	**20.49**	**0.02**	16.18	0.06
Species	14.50	0.07	13.43	0.10

Table 3

Table 3. Relation between plant descriptor parameters and pull-out variables (n = 9, one per species). Significant values are marked in bold (level of significance established at $p \leq 0.05$).).

	Max resistance				**Time to max**			
	GLM analysis		**Linear regression analysis**		**GLM analysis**		**Linear regression analysis**	
	Chi- Square	**p-value**	**R^2**	**p-value**	**Chi- Square**	**p-value**	**R^2**	**p-value**
Mean root area	2.40	0.12	0.23	0.19	2.61	0.11	0.25	0.17
Mean root biomass	**7.93**	**0.00**	**0.64**	**0.01**	1.09	0.30	0.20	0.22
Total biomass	**5.42**	**0.02**	**0.74**	**0.00**	1.69	0.19	0.28	0.15
Aerial/root biomass	1.50	0.22	0.04	0.59	1.03	0.31	0.01	0.84
Root volume	0.10	0.76	**0.70**	**0.01**	1.38	0.24	0.31	0.12
Average diameter	0.43	0.51	0.02	0.72	1.91	0.17	0.04	0.61
Root length	2.84	0.09	**0.51**	**0.03**	**8.39**	**0.00**	0.28	0.14

Figure 1 high resolution (Color)

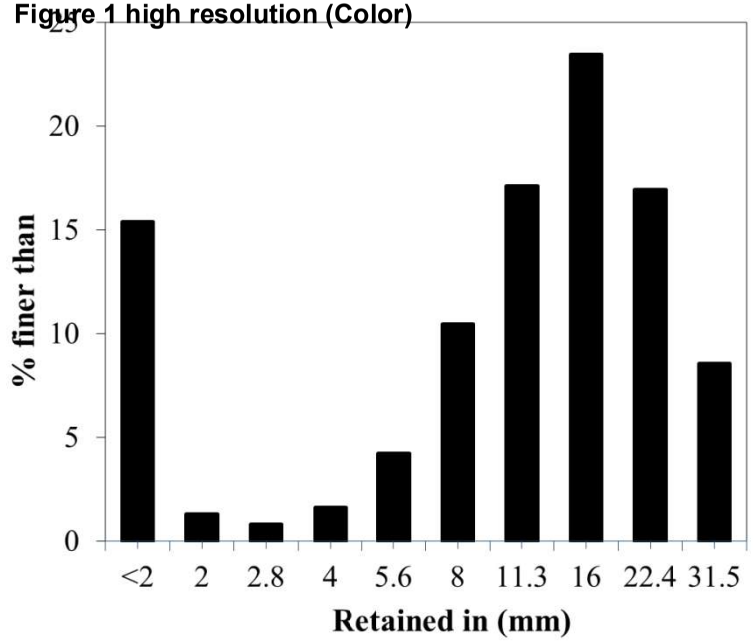
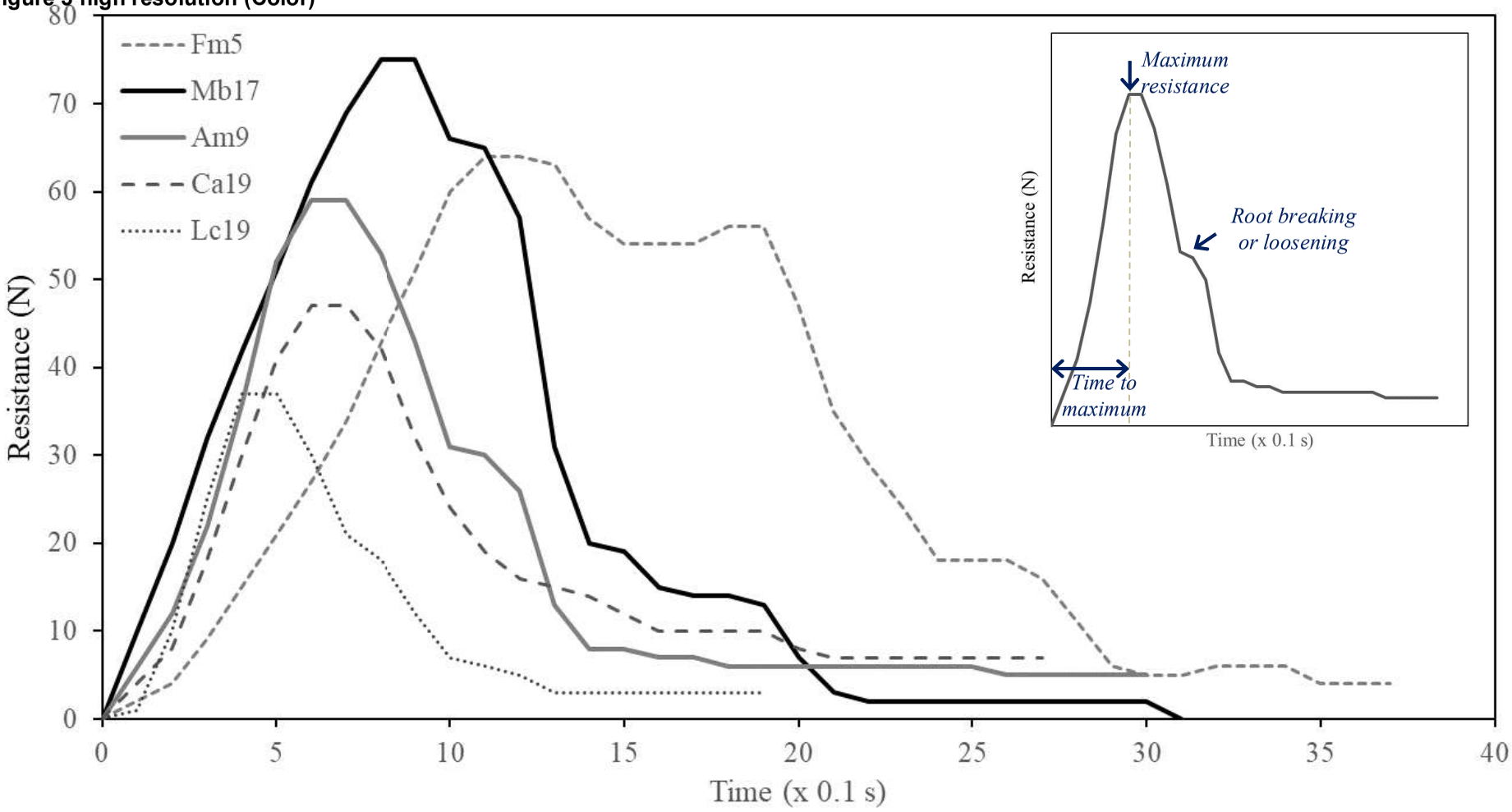


Figure 2 high resolution (Color)

Figure 3 high resolution (Color)



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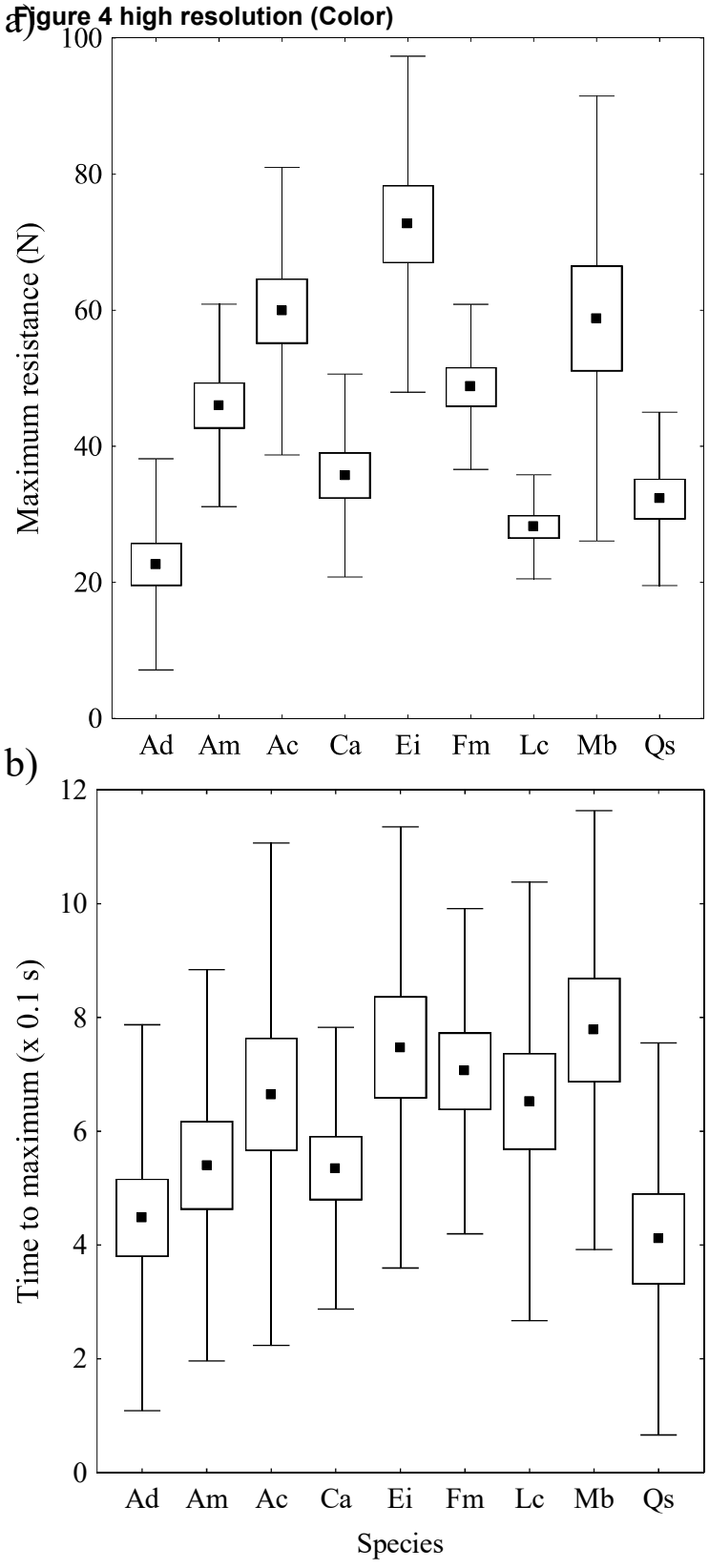

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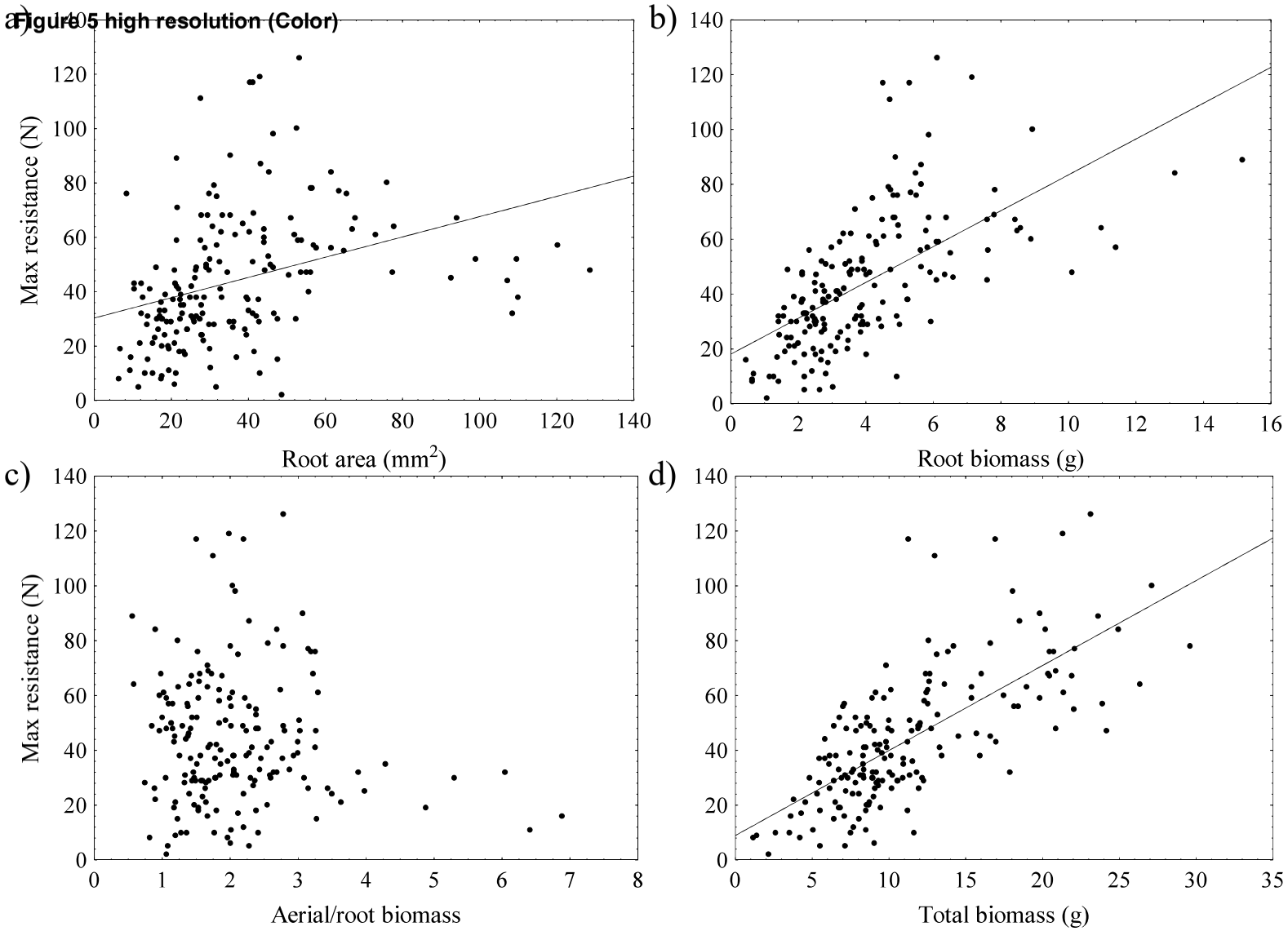

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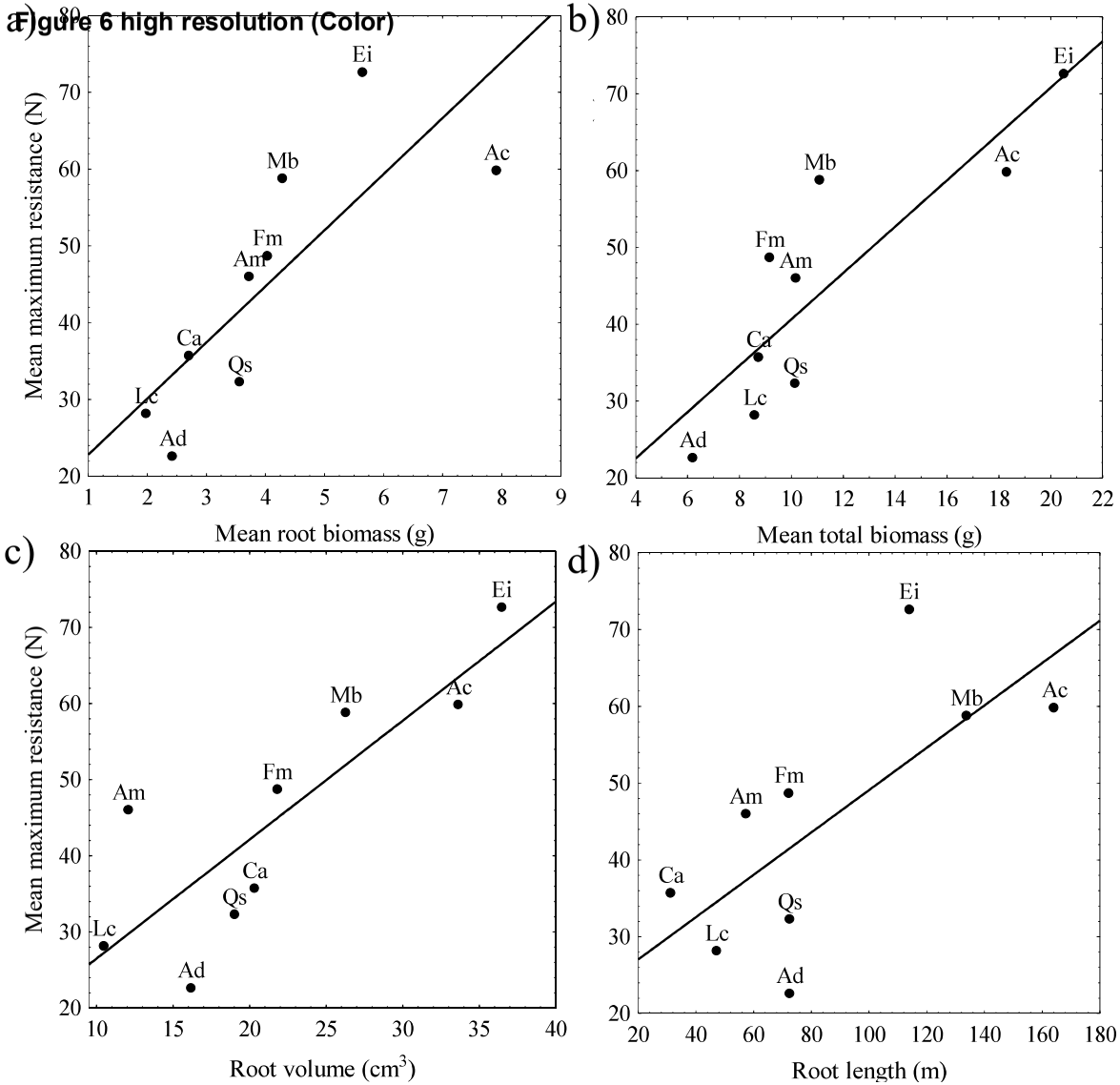

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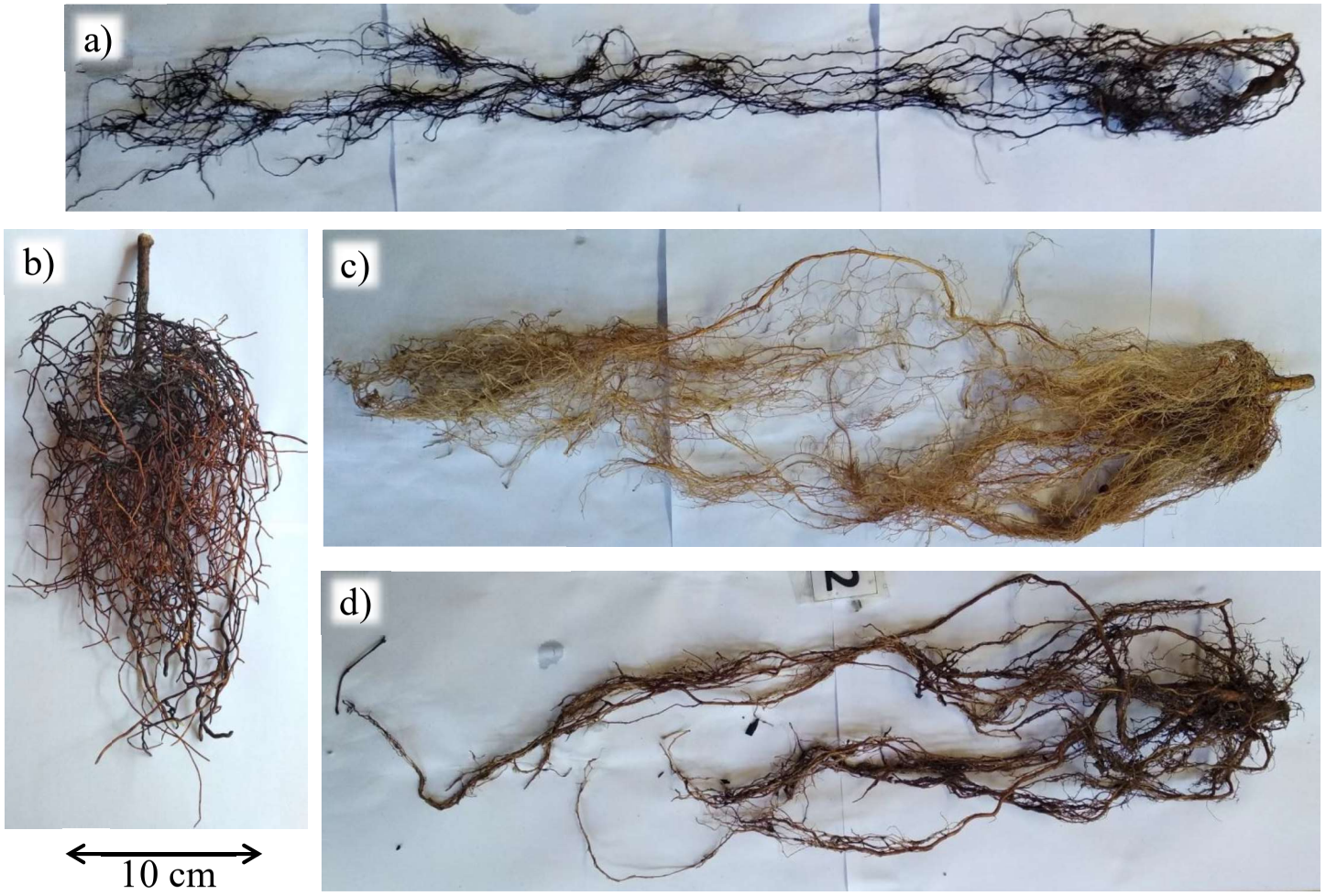
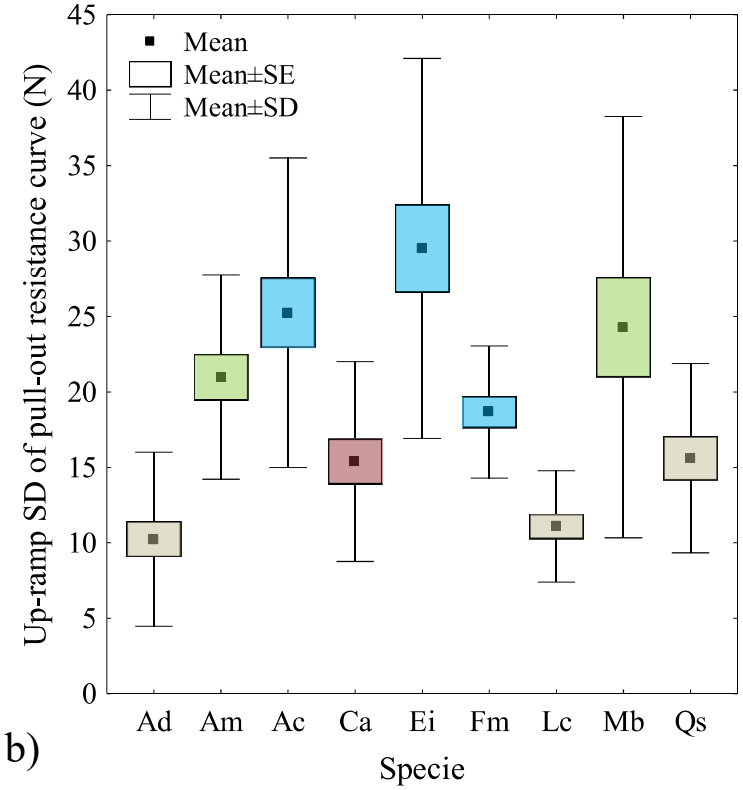


Figure 8 high resolution (Color)

a)



b)

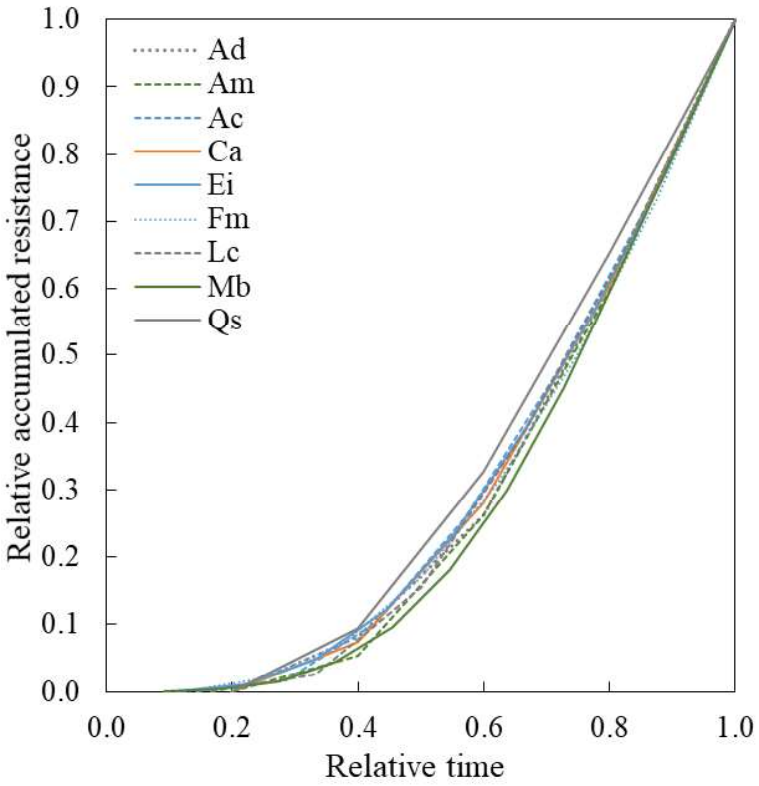
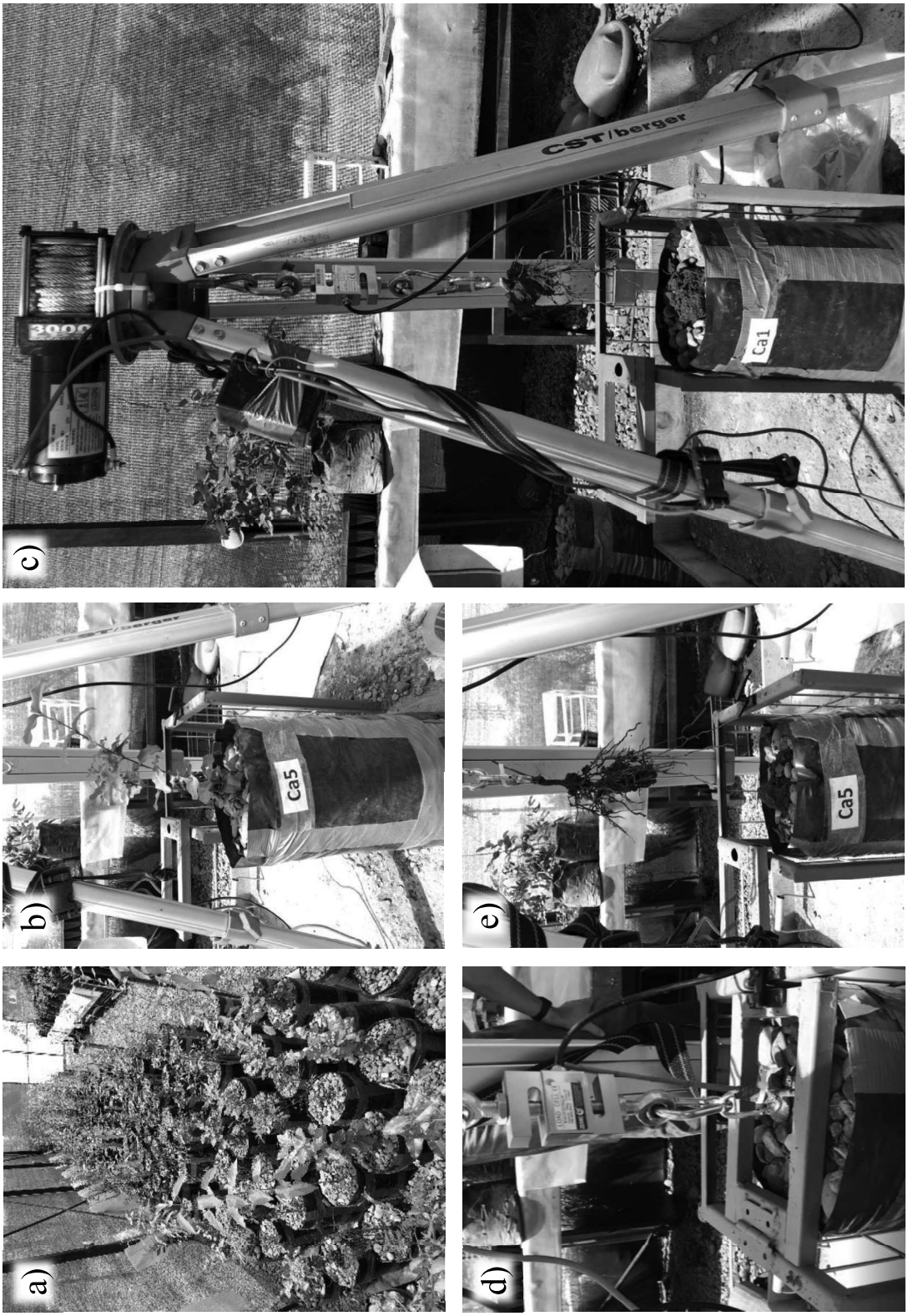


Figure 2 high resolution (Greyscale)



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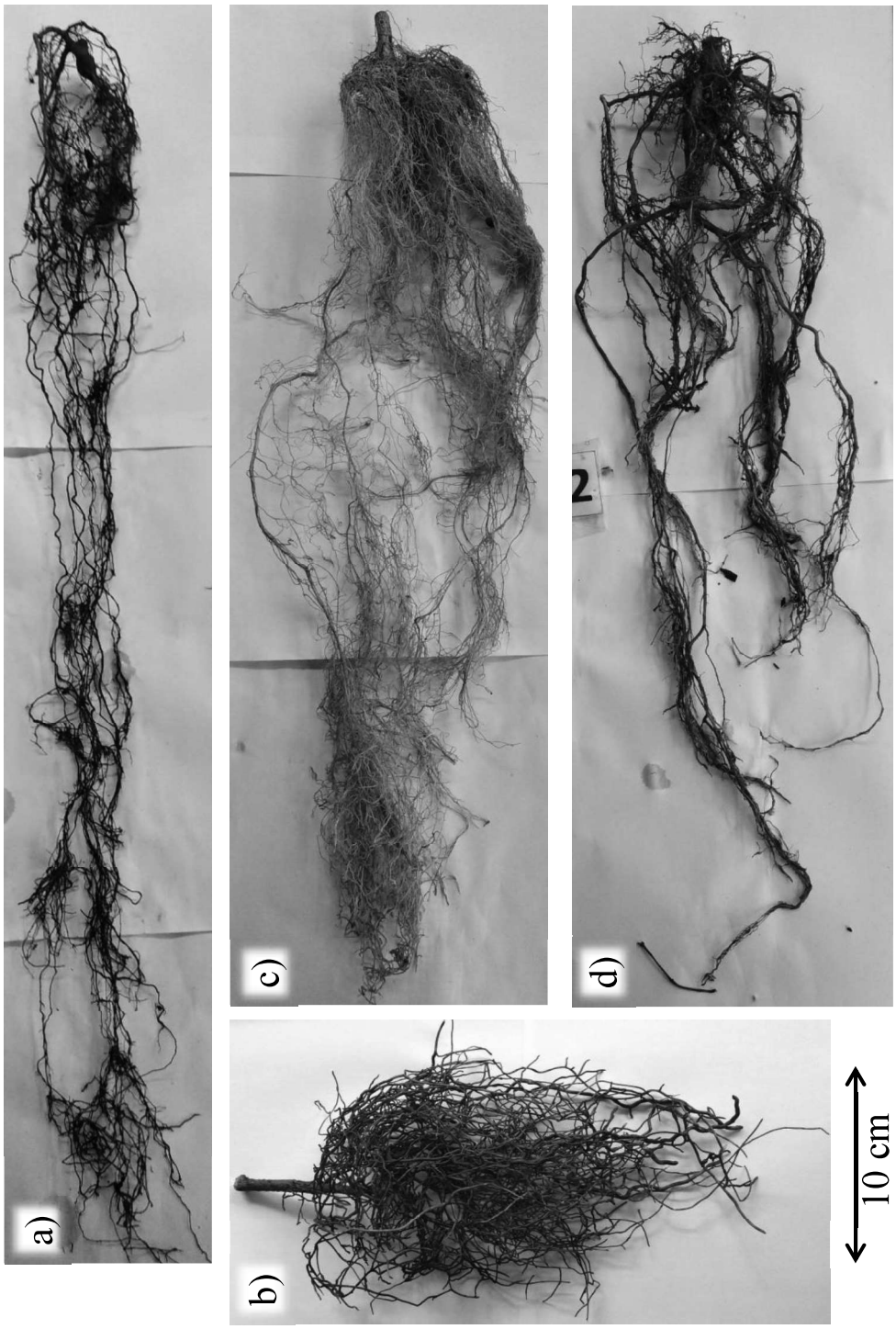

Figure 8 high resolution (Greyscale)